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Auditory feedback control for improvement of gait in patients with Multiple Sclerosis

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Abstract

Objective: To study the use of auditory feedback for gait management and rehabilitation in patients with Multiple Sclerosis (MS).
Methods: An auditory feedback cue, responding to the patient's own steps in closed-loop, was produced by a wearable motion sensor and delivered to the patient through ear phones. On-line (device on) and residual short-term therapeutic effects on walking speed and stride length were measured in fourteen randomly selected patients with gait disturbances predominantly due to cerebellar ataxia.
Results: Patients showed an average improvement of 12.84% on-line and 18.75% residually in walking speed. Average improvement in stride length was 8.30% on-line and 9.93% residually. The improvement results are particularly noteworthy when compared with the lack of change in healthy control subjects.
Conclusions: Patients with MS using auditory feedback cues showed improvement in walking abilities.

Keywords: Ambulation; Multiple Sclerosis; Rehabilitation; Auditory feedback cues; Sensory feedback; Virtual reality

1. Introduction

Positive effects of sensory cues on gait in patients with movement disorders have been reported before, particularly in the context of Parkinson's disease (PD) [1,2]. Early attempts to produce such cues artificially have resulted in open-loop systems, producing sensory cues which are independent of the patient's own motion. Open-loop systems, subject to disturbances, are inherently unstable [3]. Indeed, such systems, displaying visual objects in constant motion [4], have been found to cause confusion, related to a sense of "falling out of sync" [5]. Open-loop rhythmic auditory cues have been found to produce different responses to different rhythms and to raise issues of motivational factors [6,7]. In contrast, closed-loop visual feedback signals generated by the patient's own motion have been found to stimulate, stabilize and regulate gait [8]. A study on patients with PD [5] has shown that while open-loop stimuli have adverse effects, particularly dizziness, loss of balance, and even freezing, closed-loop visual feedback cues, responding to the patient's own movement, have a clear positive effect on gait. We have recently found a similar effect of closed-loop visual feedback on gait in patients with Multiple Sclerosis (MS), who suffer from cerebellar ataxia [9]. Previously, auditory feedback has been found to have a positive influence on postural stability in quiet standing tasks [10]. These findings suggest examining the effects of auditory feedback on gait in neurological patients. An apparatus which produces a ticking sound in response to the patient's steps, one tick per step, has been developed [11]. The patient hears the auditory cue produced by steps through

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an earphone, and can modify the auditory cue by modifying gait. A steady balanced gait will produce a pleasant auditory cue, synchronized with the patient's own steps, rewarding the patient for making the effort.

2. Methods

2.1. Subjects

Fourteen randomly selected outpatients with MS, ten women and four men, diagnosed according to the Poser criteria [11] with gait disturbances predominantly due to cerebellar ataxia, participated in the study. Exclusion criteria: auditory dysfunction and gait disturbances due to pronounced muscle weakness, spasticity, sensory ataxia, or significant general fatigue. Disease-related disability was assessed using the Kurtzke expanded disability status scale (EDSS) [12]. In addition, clinical assessment included Cerebellar Functional System Score (CFSS) which grades cerebellar function due to MS on a five grades score, in which: 0 = normal cerebellar function; 1 = abnormal signs without disability; 2 = mild ataxia; 3 = moderate ataxia; 4 = severe ataxia in all limbs or trunk; 5 = unable to perform coordinated movement due to ataxia.

2.2. Ambulation assessment

Assessment of patient ambulation, conducted by an impartial independent investigator, was carried out using the ambulation parameters of walking speed (meters/second) and stride length (meters). The control group consisted of eleven healthy individuals. The study was approved by the institutional Helsinki committee and informed consent was obtained from each of the participants once the nature of the procedures had been fully explained. Clinical and personal data of patients and control groups are presented in Table 1.

Table 1

Clinical characteristics of patients and control groups

MS patient group						Control group		
Patient	Sex	Age	DD	EDSS	CFSS	Subject	Sex	Age
1	W	46	18	6	4	1	M	26
2	M	55	24	6	4	2	M	27
3	W	48	3	5	4	3	W	28
4	W	59	5	4	3	4	W	23
5	W	56	1.5	4	2.5	5	W	26
6	M	31	10	4.5	3	6	M	25
7	W	50	6	6	4	7	W	23
8	W	45	5	3.5	3	8	W	23
9	W	49	2	4.5	3	9	M	24
10	W	54	10	4.5	3.5	10	M	28
11	W	54	12	5.5	4	11	W	27
12	W	33	5	5.5	3.5			
13	M	49	21	3.5	2.5			
14	M	51	3	4	3			

(DD = disease duration in years; EDSS = Expanded Disability Status Scale; CFSS = Cerebellar Functional System Score).

Fig. 1. Auditory feedback apparatus used in tests.

2.3. Auditory feedback apparatus and mode of assessment

Auditory cues were generated by a device, shown in Fig. 1, which sounds, through a head-set or an ear piece, a tick each time the user takes a step. A belt-mounted box, the size and weight of a small cell-phone, contains a motion sensor, a micro-controller and software, which implements an adaptive filter for transforming the user's movement into sound. The user, in turn, adjusts gait so as to produce a balanced rhythmic auditory cue. The expected result is an improved gait pattern.

2.4. Procedure

All tests were performed at the Multiple Sclerosis Center, Carmel Medical Center, Haifa, Israel, at about the same daytime. Examination of each patient comprised four stages, each consisting of the patient walking a straight track of 10 m: baseline, device off, device on, and residual effects, as hereinafter:

Stage 1: The ambulation parameters, baseline walking speed and stride length were measured first, without the device. The patient was verbally instructed to "walk normally". The time to complete the 10-meter track and the number of steps were recorded four times and averaged.
Stage 2: The device was turned on. The patient was instructed to walk so as to make the auditory cue as rhythmic as possible along the 10-meter track. Walking speed and stride length were measured four times and averaged.
Stage 3: The device was taken off the patient, who was given a ten-minute break. After the break, the patient was instructed to "walk normally" the 10-meter track without the device. Walking speed and stride length were recorded four times and averaged. The purpose of this stage was to measure the residual short-term therapeutic effect of auditory feedback.

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3. Results

3.1. Clinical features, baseline parameters and on-line improvement

The test results for the patients and the control subjects are summarized in Table 2. Baseline walking speed and stride length of patients before using the device are presented. Walking speed and stride length of patients using the device are specified in the "on-line" column, along with percentage changes from "baseline" to "device on". Walking speed and stride length after the break, without the device, are given in the "residual effect" columns, along with percentage changes with respect to the baseline walking speed and stride length.

The percentage improvement in the on-line walking speed of the patients and of the controls with respect to the baseline walking speed is depicted for comparison in Fig. 2. Similarly, the residual improvement of the two groups is depicted in Fig. 3.

For the patient group, the on-line walking speed improved, on average, 12.84% (standard deviation 18.74%). On-line average improvement in stride length was 8.30% (standard deviation 11.87%). The results for the controls did not show any particular trend in relation to the baseline walking speed or stride length. Furthermore, using the device did not improve performance, due to the burdening effect of wearing the device. Indeed, it was found that the on-line walking speed changed, on average,

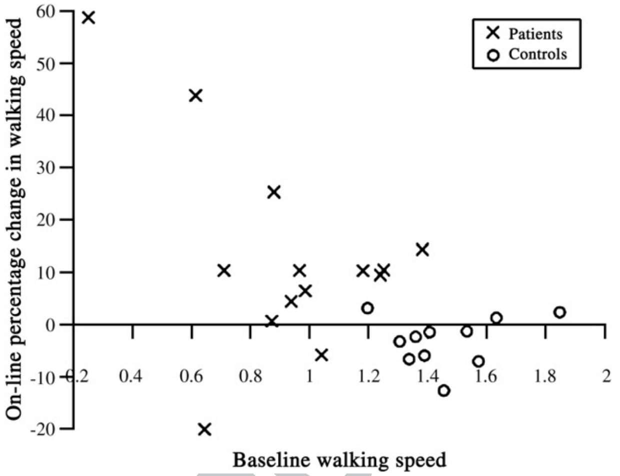

Fig. 2. On-line percentage improvement in the walking speed of MS patients and control subjects as a function of the baseline walking speed.

Table 2
Test results for MS patients and for control subjects: walking speed (meters/second), and stride length (meters)

Patient no.	Baseline ambulation		On-line				Residual			
			Device on		Percentage change		Device off		Percentage change	
	Walking speed	Stride length	Walking speed	Stride length	Walking speed	Stride length	Walking speed	Stride length	Walking speed	Stride length
MS patients										
1	0.252	0.256	0.400	0.333	58.73%	30.01%	0.361	0.312	43.25%	21.86%
2	0.647	0.444	0.493	0.435	−19.97%	−15.20%	0.684	0.526	5.72%	18.47%
3	1.043	0.513	0.984	0.541	−5.66%	5.46%	1.211	0.588	16.11%	6.29%
4	1.381	0.690	1.581	0.714	14.48%	3.48%	1.616	0.714	17.02%	3.28%
5	0.880	0.556	1.103	0.597	25.35%	7.37%	1.044	0.588	18.64%	5.76%
6	0.941	0.571	0.982	0.625	4.36%	9.46%	0.933	0.555	−0.85%	−2.80%
7	0.712	0.476	0.786	0.488	10.39%	2.52%	0.798	0.476	12.10%	0.00%
8	1.185	0.588	1.306	0.625	10.21%	6.29%	1.307	0.625	10.30%	6.29%
9	0.871	0.487	0.877	0.500	0.68%	2.67%	0.912	0.500	4.71%	2.67%
10	0.966	0.500	1.067	0.555	10.46%	11.00%	1.104	0.555	14.29%	11.00%
11	0.987	0.526	1.053	0.526	6.69%	0.00%	1.267	0.571	28.37%	8.56%
12	0.616	0.333	0.886	0.444	43.83%	33.33%	0.859	0.426	39.45%	27.93%
13	1.243	0.769	1.362	0.833	9.57%	8.32%	1.815	0.909	46.02%	18.21%
14	1.253	0.690	1.386	0.769	10.61%	11.45%	1.346	0.769	7.42%	11.45%
Control subjects										
1	1.361	0.769	1.298	0.769	−2.27%	0.00%	1.398	0.800	2.66%	4.00%
2	1.340	0.714	1.278	0.714	−6.58%	0.00%	1.407	0.714	5.07%	0.00%
3	1.852	0.833	1.953	0.833	2.54%	0.00%	1.890	0.833	2.08%	0.00%
4	1.576	0.714	1.500	0.769	−6.98%	7.69%	1.637	0.714	3.85%	0.00%
5	1.457	0.800	1.302	0.769	−12.83%	−3.85%	1.517	0.800	4.17%	0.00%
6	1.534	0.833	1.489	0.769	−1.04%	0.00%	1.572	0.769	2.52%	−7.69%
7	1.638	0.769	1.569	0.769	1.33%	0.00%	1.625	0.769	−0.81%	0.00%
8	1.408	0.667	1.420	0.690	−1.35%	3.45%	1.517	0.714	7.74%	7.14%
9	1.202	0.714	1.222	0.714	3.05%	0.00%	1.271	0.714	5.72%	0.00%
10	1.393	0.714	1.173	0.667	−5.92%	0.00%	1.284	0.667	−7.83%	−6.67%
11	1.308	0.667	1.311	0.667	−3.21%	−3.33%	1.329	0.667	1.59%	0.00%

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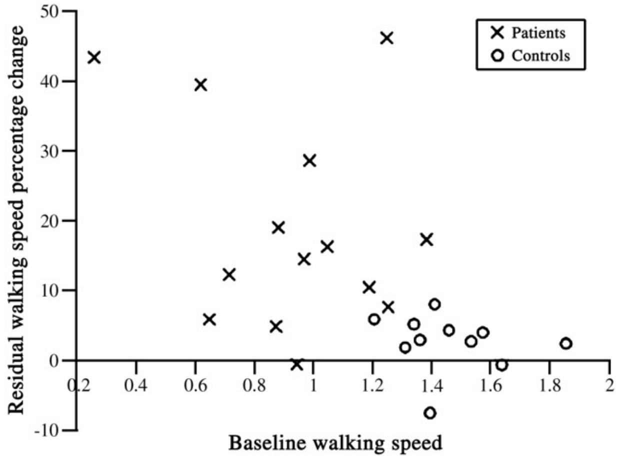

Fig. 3. Residual (short-term therapeutic) percentage improvement in the walking speed of MS patients and control subjects as a function of the baseline walking speed.

by −3.02% (standard deviation 4.76%). As in the case of the walking speed, there was no particular trend in the on-line percentage improvement in the stride length as a function of the BSL in the controls. The on-line average change in the stride length was also negligible (0.36%, with standard deviation 3.09%). It can be seen that the level of variation (or standard deviation) in the performance results among patients and among controls is similar to the level of average improvement in performance.

3.2. Residual improvement

The residual improvement in the walking speed (Fig. 3) was, on average, 18.75% (standard deviation 18.53%). Average residual improvement in stride length was 9.93% (standard deviation 9.46%). In contrast, there was no significant residual improvement in the walking speed and the stride length of the controls (2.43% and −0.29%, with standard deviations 4.09% and 4.11%, respectively). Again, it can be seen that the level of variation is close to that of the average improvement.

4. Discussion

The mechanism by which auditory signals assist in coordinating rhythmic or sequential movements remains to be determined. There appears to be some evidence that rhythmic sound patterns can increase the excitability of spinal motor neurons via the reticulospinal pathway, thereby reducing the amount of time required for the muscles to respond to a given motor command [13]. There is also increasing evidence that the basal ganglia has an important role in the proper sequencing of complex movements [14]. Studies in monkeys have shown that movement related phasic discharge of pallidal neurons may serve as an internal cue to the supplementary motor area signaling the end of one movement and allowing the onset of the next [15]. These mechanisms do not necessarily hold the key to movement disorders in MS, where the problem is predominantly in the white matter and not in the gray matter. Furthermore, while the basal ganglia and the pallidum may play a role in certain movement disorders such as Parkinson's disease [16], the connection of the basal ganglia to ataxia, which is predominantly related to brainstem–cerebellar connections, is not clear. Yet, studies of neuronal substrates and mechanisms for auditory motor control may lead to strategies for gait management and rehabilitation in MS.

Open-loop verbal instructional cues [17] and rhythmic auditory cues [6,7] have been used for gait management in patients with PD. However, open-loop rhythmic cues raise the question of which rhythm would suit a given patient at a given time (for instance a rhythm 10% faster than the baseline [5] may suit most, but not all patients). In addition, repeated use of rhythmic sound of relatively low complexity is assumed to induce a great amount of redundancy into the perceptual process and thus strongly reduce effective arousal effects related to motivation [6,7]. A study on the role of auditory feedback in maintaining postural balance in stance [18] suggests that auditory feedback increases postural stability in quiet standing tasks and results in a more prominent role for feedback (closed-loop) control over feed-forward (open-loop) control. Furthermore, it indicates that the solution proposed by the brain with auditory feedback seems to involve more feedback control for a more stable sway. A comparison with visual feedback control of upright quiet stance [19] suggests non-redundant roles in multi-sensory integration for the control of posture. Whereas vision provides information about the external environment and allows prediction of forthcoming events, auditory information processing time is markedly faster than visual reaction times, making it more important for postural reaction to disturbing stimuli [19], that is, stability feedback control. It should also be noted that an augmented auditory feedback device, employing a pressure sensitive foot-switch, has been proposed for the treatment of equines (toe-walking) gait in children [20]. Auditory feedback influences gait by creating an external cue, which serves as a reference for the patient. However, the feedback nature of this external cue makes it non-imposing, as it is fully controlled by the patient. It creates, on the one hand, a constant awareness of gait quality, and, on the other, an instantaneous sensory response to changes in gait quality. The patient, by own control, then makes an effort to improve gait quality, and is, in turn, informed of any improvement (or deterioration) in gait quality by changes in the auditory cue.

The present study indicates that auditory feedback can help patients with MS control their gait. Patients with baseline performance below the median show a considerably higher improvement than patients above the median. In other words, the more room there is for improvement, the more

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improvement there is. Compared to our previous study [9], the present results show some notable differences between the effects of visual and auditory feedback. On average, gait improvement due to auditory feedback was higher than that achieved by visual feedback, which may require more elaborate information processing by the brain [19]. While visual feedback produced a higher improvement in stride length than in walking speed, the improvement in walking speed due to auditory feedback was higher than the improvement in stride length. The higher improvement in stride length caused by visual feedback can be attributed to the bio-feedback effect of visually reaching a given target, that is, the edge of a tile, by extending the foot farther. On the other hand, the higher walking speed caused by auditory feedback reinforces earlier findings that auditory signals reduce reaction time in a voluntary motor task [10]. Relative to the baseline performance, the residual improvement is even greater than the on-line improvement. This is explained by the fact that there was no off-line training involved. Removing the burdening effect of the device, combined with the learning gained while using the device, maximizes the immediate residual performance. The relatively large short-term residual improvement in patients using auditory feedback is particularly encouraging, as it suggests a therapeutic potential. The improvements in performance seem particularly noteworthy when compared to the results obtained for the controls, which showed no meaningful improvement. This suggests that an improved device, reducing the burdening effect, and extended training, may further improve patient performance.

Audio-based assistive technology may have special importance in reinforcement of functions in patients who suffer from visual impairment (and are therefore not candidates for the visual system) and patients suffering from proprioceptive input problems. Since the auditory and the vision feedback channels seem to produce somewhat complementary functional enhancement properties, and since, as suggested by earlier studies [19], multi-sensory integration may be key to motor stabilization and control, future studies may examine the effects of simultaneous visual and audio feedback through various artificial means on walking abilities of MS and other neurological patients. Future studies may also examine the combined long term therapeutic effects of visual and audio feedback on gait in movement disorder patients. The analysis of larger groups of patients would facilitate a comparison between patient subcategories, responders and non-responders to sensory feedback in particular, and a determination of specific predictive factors.

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